



Available online at

**ScienceDirect**  
www.sciencedirect.com

Elsevier Masson France

**EM|consulte**  
www.em-consulte.com/en



## CLINICAL RESEARCH

# The future of transcatheter pulmonary valvulation



Le futur de la valvulation pulmonaire percutanée

Zakaria Jalal<sup>a,b</sup>, Jean-Benoit Thambo<sup>a,b,c</sup>,  
Younes Boudjemline<sup>a,d,e,\*</sup>

<sup>a</sup> Groupe de cathétérisme interventionnel pédiatrique et congénitale (GCIPC), filiale de cardiologie pédiatrique et congénitale de la Société française de cardiologie, 75015 Paris, France

<sup>b</sup> University Hospital of Bordeaux, Department of Paediatric and Adult Congenital Heart Defects, 33604 Pessac, France

<sup>c</sup> Université Victor-Segalen, 33076 Bordeaux, France

<sup>d</sup> Centre de référence malformations cardiaques congénitales complexes, M3C, Necker Hospital for Sick Children, Assistance Publique des Hôpitaux de Paris, Paediatric Cardiology, 75015 Paris, France

<sup>e</sup> Université Paris Descartes, Sorbonne Paris Cité, 75006 Paris, France

Received 12 June 2014; received in revised form 30 June 2014; accepted 1st July 2014  
Available online 16 September 2014

### KEYWORDS

Congenital heart disease;  
Percutaneous pulmonary valve implantation;  
Melody® valve

**Summary** Percutaneous pulmonary valve implantation now has a key role in the setting of dysfunctional right ventricle-to-pulmonary artery conduits or failing bioprosthetic pulmonary valves. However, despite the excellent results obtained with the two devices available currently (the Melody® valve [Medtronic Inc., Minneapolis, MN, USA] and the Edwards SAPIEN® valve [Edwards Lifesciences, Irvine, CA, USA]), many patients eligible for pulmonary valve replacement remain unsuitable for percutaneous pulmonary valve implantation, mainly because of large native outflow tracts. Accordingly, one of the major challenges for the future is to expand percutaneous pulmonary valve implantation to a broader population of patients. Moving forward, there is important ongoing research that is intended to improve patient outcomes, expand percutaneous pulmonary valve implantation therapy and continue to reduce the number of open-heart surgeries in this population. In this review, we underline the limitations and issues

**Abbreviations:** MRI, Magnetic resonance imaging; PPVI, Percutaneous pulmonary valve implantation; PVR, Pulmonary valve replacement; RVOT, right ventricular outflow tract.

\* Corresponding author. Service de cardiologie pédiatrique, hôpital Necker–Enfants-Malades, 149, rue de Sèvres, 75015 Paris, France.  
E-mail address: [younes.boudjemline@nck.aphp.fr](mailto:younes.boudjemline@nck.aphp.fr) (Y. Boudjemline).

<http://dx.doi.org/10.1016/j.acvd.2014.07.046>

1875-2136/© 2014 Elsevier Masson SAS. All rights reserved.

## MOTS CLÉS

Cardiopathies  
congénitales ;  
Remplacement  
valvulaire pulmonaire  
percutané ;  
Melody®

associated with the devices available currently, and we focus on the development of new strategies (such as hybrid approaches or magnetic resonance-guided procedures), new devices (such as right ventricular outflow tract reducers or the novel Native Outflow Tract valved stent from Medtronic) and new technologies (such as tissue-engineered valves), which may help to take up these challenges and represent the future of transcatheter valve implantation.  
© 2014 Elsevier Masson SAS. All rights reserved.

**Résumé** Le remplacement valvulaire pulmonaire percutané a désormais un rôle clé dans la prise en charge des dysfonctions de conduits entre le ventricule droit et l'artère pulmonaire ou de bioprothèses pulmonaires. Cependant, malgré les excellents résultats obtenus avec les prothèses percutanées actuellement disponibles (Melody® [Medtronic Inc., Minneapolis, MN, États-Unis] et Edwards SAPIEN® [Edwards Lifesciences, Irvine, CA, États-Unis]), de nombreux patients nécessitant un remplacement valvulaire pulmonaire ne sont pas éligible pour cette technique percutanée, essentiellement du fait d'une large voie droite native. De ce fait, un des principaux défis pour l'avenir est d'étendre l'implantation valvulaire percutanée à une plus large proportion de patients. Il existe ainsi un important champ de recherche ayant pour but d'améliorer le devenir des patients, d'étendre les indications de cette thérapie et de continuer de réduire le nombre de chirurgies dans cette population. Dans cette revue, nous souligneront les principales limites des dispositifs actuels et nous nous focaliseront sur le développement de nouvelles stratégies (comme les procédures hybrides ou les procédures guidées par IRM), de nouveaux dispositifs (comme les réducteurs de taille de voie droite ou la nouvelle prothèse Native Outflow Tract de Medtronic) et de nouvelles technologies (stents valvés créés par bio-engineering) qui pourraient permettre de relever ces challenges et constitueront le futur du remplacement valvulaire pulmonaire percutané.  
© 2014 Elsevier Masson SAS. Tous droits réservés.

## Introduction

Patients with complex congenital heart defects are subject to numerous open-heart surgeries, usually performed to relieve right ventricular outflow tract (RVOT) abnormalities, with incremental risks and significant morbidity. In September 2000, the first successful percutaneous pulmonary valve implantation (PPVI) was performed, using a bovine jugular vein sutured on a platinum stent [1]. Since this first-in-man report, catheter-based valve implantation has evolved rapidly over the last decade. This novel treatment option has changed the culture of paediatric cardiology, adult cardiology and cardiovascular surgery. Moreover, it has modified the way in which the expectant family of a foetus likely to undergo several RVOT surgeries is counselled [2].

Currently, there are two devices used for PPVI: the Melody® valve (Medtronic Inc., Minneapolis, MN, USA), a bovine jugular vein valve sutured within a platinum and iridium stent; and the Edwards SAPIEN® valve (Edwards Lifesciences, Irvine, CA, USA), made of bovine pericardium mounted in a rigid stainless steel stent, although the SAPIEN valve is not widely available. Multiple studies have demonstrated that PPVI with the Melody valve is safe and effective, with a high rate of procedural success, and durable in short- and medium-term follow-up in properly selected patients [3,4]. The SAPIEN transcatheter heart valve is an alternative device with similar safety and efficacy in limited studies [5,6]. PPVI with these revolutionary devices provides a non-surgical alternative in the treatment of dysfunctional RVOT

and allows a reduction in the number of open-heart surgeries in these patients.

However, despite these excellent results, the heterogeneity of this population and the wide variety of implantation site morphologies, sizes and dynamics, limits the suitability of PPVI to approximately 15% of patients who require pulmonary valve replacement (PVR), indicating surgical PVR in 85% of patients [7]. Accordingly, one of the major challenges for the future is to expand PPVI to a broader population of patients, including those with large and/or patched RVOTs or complex lesions with a vulnerable neighbourhood, and small children.

Several authors have described advanced techniques or device modifications to make these patients suitable for the transcatheter technique [8–10]. The hybrid approach, including strategies to surgically and/or percutaneously prepare the outflow tract for subsequent transcatheter valve deployment, is another key area of pulmonary valvulation development.

Furthermore, extensive research and development is being conducted to design a suitable transcatheter valve for patients with a dysfunctional native or patched RVOT, typically with significant pulmonary regurgitation rather than obstruction, which is too large for the devices available currently. The first-in-human implantation of a large RVOT transcatheter valve developed by Medtronic was reported in 2010 [11].

In this review we aim to: underline the limitations and issues associated with the Melody and SAPIEN valved stents; focus on the alternative techniques and approaches that

allow effective PPVI with these valves; and describe the ongoing research into and design of new transcatheter pulmonary devices.

## Percutaneous pulmonary valve implantation in large right ventricular outflow tract

Current transcatheter pulmonary valves have demonstrated a high rate of procedural success with acceptable safety profiles and favourable outcomes. However, of the patients with a clinical indication for PVR, only 15% can be treated with the devices available currently, indicating surgical PVR in 85% of patients, as they have a history of transannular patch reconstruction of the RVOT, leading to distortion and dilation of that region and precluding PPVI because of the absence of an appropriate landing zone (16–24 mm for the Melody valve; 21–27 mm for the SAPIEN valve) [7,12,13].

To extend PPVI indications, some authors started to propose valve implantation in selected native outflow tracts with stenotic and/or non-distensible physiology [14]. Other reports described advanced techniques to make these patients suitable for the transcatheter technique (i.e. the use of two Melody valves implanted in respective pulmonary arteries in a single patient; jailing and/or Russian doll techniques) [9,15–17]. Cheatham et al. showed that PPVI using a 24 mm balloon catheter for the deployment of the Melody valve was feasible, without impairment of valvular function (RVOT diameter of 26 mm) [18]. The SAPIEN valve diameters are 23, 26 and 29 mm, which makes it potentially more suitable for PPVI in large-diameter conduits and native outflow tracts (up to 27 mm) than the Melody valve, but the device is not widely available.

Nevertheless, most patients with transannular patch repair have a dilated and distensible RVOT, making device embolization a concern in this population. Accordingly, there is worldwide interest in developing new strategies with the current devices and/or a new design of transcatheter heart valve to make these patients suitable for PPVI, avoiding the risk of surgical PVR.

## A new transcatheter pulmonary valve

The first-in-human implantation of a new self-expandable transcatheter pulmonary valve was reported in 2010 [11]. This was done under compassionate use in a 42-year-old man with pulmonary insufficiency. The device design was tested in animals and modified to fit the patient's anatomy and to allow safe implantation. The authors did computed tomography of the patient's RVOT to create prototyping models to customise and test the device, which was successfully implanted into the patient with a satisfactory result. No stent fracture and only trivial paravalvular leak were observed at 6-month follow-up. This new prosthesis is called the Native Outflow Tract device (Medtronic Inc., Minneapolis, MN, USA). Besides the use of porcine pericardium to make the valve, the main modifications to this valved stent, compared with the Melody and SAPIEN valves, are an hourglass geometry (i.e. larger diameters at the proximal and distal end; smaller diameters in the central portion holding the

valve) and the use of a self-expanding nitinol stent with a polymeric graft, which should help the stability of the device in various RVOT anatomies (Fig. 1).

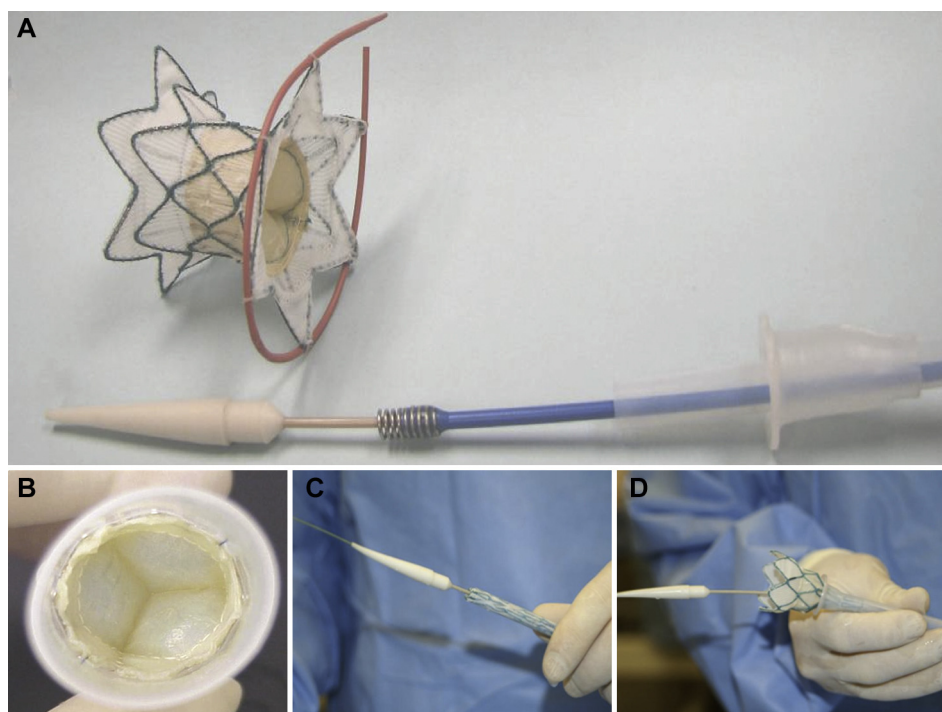
An Investigational Device Exemption trial of the Native Outflow Tract device has been enrolling subjects since April 2013 (clinicaltrials.gov identifier: NCT01762124; 10 patients enrolled so far). Given the limitations in the animal model regarding confirmation of device boundary conditions, this feasibility study aims to characterize that information as well as to evaluate safety, procedural feasibility and performance data, which will be used in the future development of the device. This innovative device may be the future of PPVI. However, regarding the wide anatomical variability of the RVOT and the frequently associated pulmonary artery disease encountered in this patient population, alternative techniques allowing valve replacement are still being explored by investigators [19]. Another device (Venous P Valve; Medtech, Shenzhen, China) is presently under investigation; 18 patients have been implanted in China, India and Thailand, but no data have been published so far. A European study should start before the end of 2015.

Finally, one major innovation in PPVI may be the development of repositionable valved stents and low-profile devices. The Lotus Valve System® (Boston Scientific Corporation, Natick, MA, USA), a bovine pericardial valve attached to a braided nitinol stent used for transcatheter aortic valve replacement, features this specific function. The braided nitinol frame has a locking system that allows controlled precise deployment, recapture and subsequent repositioning or removal, as necessary [20].

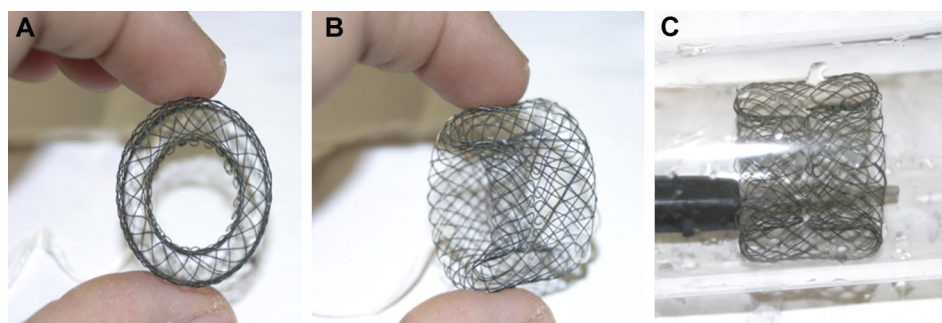
## RVOT reducers

Patients who underwent surgical repair of tetralogy of Fallot during infancy using a transannular patch can have large pulmonary trunks that often exceed 30 mm in diameter, making PPVI technically unfeasible with the current valves. To extend the indications of PPVI, the use of percutaneously implanted RVOT size reducers has been described. Boudjemline et al. designed and developed several versions of a preshaped self-expandable stent, forming a covered double cylinder, with the internal diameter calibrated to authorize implantation of available valved stents. The device is available with various external diameters (30–40 mm; Fig. 2). This device was implanted in sheep ( $n=30$ ) that had previously had surgical RVOT enlargement. During the same procedure, a valved stent (bovine jugular vein) was subsequently deployed in the central part of the filler. The main complications were device embolization ( $n=1$ ) and paravalvular leaks (6/24 animals; 25%). The leak was related to undersizing of the device. Indeed, 5/6 leaks (83%) occurred in animals where the size of the device was less than 5 mm larger than the pulmonary artery diameter ( $P<0.05$ ), which confirms that oversizing the device is mandatory for stent anchoring and ultimately for definitive fixation to the vascular wall [21–23].

Other authors have reported on the development of a self-expandable nitinol stent, inside which is attached a specifically designed polyester graft (a central tube, 20 mm in diameter, with two flared extremities), which has been successfully implanted in sheep ( $n=6$ ) [24]. During the same procedure, a 20 mm nitinol valved stent (bovine



**Figure 1.** Native Outflow Tract transcatheter pulmonary valve device (Medtronic Inc., Minneapolis, MN, USA). A. Lateral view of the nitinol self-expandable stent with an hourglass geometry and the valved-stent delivery system. B. Closed porcine pericardial valve leaflets. C. and D. Valved stent (C) charged in the delivery system and (D) partially deployed.



**Figure 2.** RVOT reducer. Latest version of the RVOT reducer developed by Boudjemline et al., shown uncovered. A. and B. Front and oblique view of the device; the extremities are directed inward and back toward an intermediate position forming a second wall in parallel with the external one. C. Lateral view of the deployed device in a plastic tube.

pericardium) was implanted within the deployed size reducer. These devices seem very promising, but they have not been tested for human application so far. Indeed, the applicability of these devices to the human anatomy with calcified RVOT or non-circular cross-sectional shape remains to be proven.

### Percutaneous pulmonary valve implantation in small children and those with a low body weight

The transcatheter valves available currently (the Melody and SAPIEN valves) require a large delivery sheath (22 and 24 Fr, respectively), limiting the use of this technology in patients

weighing > 30 kg. A recent study focused on PPVI results with the Melody valve in this specific population [25]. Twenty-five children (median age, 8 years; median weight, 21.4 kg) were scheduled for PPVI in conduits ranging from 12 to 23 mm, using a standard technique and devices. Vascular access was by means of the femoral vein ( $n = 17$ ), the right internal jugular vein ( $n = 6$ ) or the left subclavian vein ( $n = 2$ ). PPVI was feasible in all but two patients (risk of coronary compression in one; inability to advance the delivery sheath through the common femoral vein in the other). Post-PPVI results showed good valve function. This report underlines that PPVI is feasible in children weighing < 30 kg with good procedural and haemodynamic results. However, the population sample size and short follow-up limit the statistical significance of such results. Furthermore, procedural adverse events were relatively common, although they had already been reported



in the same proportions in studies with larger patients [4]. Nevertheless, it is probable that small patients are at risk of some complications related to the size and stiffness of the delivery system and vascular access issues.

Although the optimal timing for intervention in RVOT conduit dysfunction remains unclear, there is a trend towards earlier intervention in the paediatric population, to minimize deleterious effects of conduit failure on right ventricular function [26,27].

As technology continues to advance, minimizing the delivery sheath and valve size, and developing mini-invasive hybrid approaches should be prioritized, so that this technology can be used in younger patient populations. New devices with reduced delivery systems are under development at the moment. The most advanced device is based on a dry valve mounted on a stent. The whole system comes prepared, already mounted in the delivery system and in the same package. The valve being dry, the delivery system is only 14Fr, making the use of this device possible in small children.

## 'Think hybrid'

### Hybrid procedures

Hybrid procedures involving the use of surgical and transcatheter techniques are increasingly common in the field of congenital heart diseases, leading to optimized efficacy and safety when conducting at-risk procedures [28]. Hybrid approaches need a collaborative relationship between cardiac surgeons and interventionists, especially during the preprocedural work-up to assess patient suitability and choose the appropriate technique. Furthermore, while the advantage of PPVI is to avoid repeated open-heart surgeries, the ideal hybrid procedure should be as minimally invasive as possible.

In the field of transcatheter PVR, animal and human hybrid procedures mostly aimed to perform valve implantation in large RVOTs. A few years after the first PPVI, the Necker Hospital for Sick Children group (Paris, France) reported off-pump PVR using a combined approach in ewes. A left thoracotomy was first performed, then the main pulmonary artery was banded using two radiopaque rings of nitinol, giving a reduction in RVOT diameter from 30 to 17.6 mm. Subsequent PVR through a percutaneous or transventricular approach was then performed without extracorporeal circulation, using an 18-mm bovine jugular venous valve mounted in a balloon-expandable stent [29]. In line with these trials on valve implantation into the pulmonary position, first results described modified valve delivery into the aortic or mitral position [30].

Furthermore, Schreiber et al. published another approach, which allows implantation of a Shelhigh valve (Shelhigh inject, Shelhigh Inc., Union, NJ, USA) – a porcine pulmonic valve mounted inside a self-expandable stent covered with porcine pericardium, with a diameter as long as 31 mm – without the use of cardiopulmonary bypass, in 6 patients operated on with a transannular patch [31]. The valve was introduced just beneath the RVOT. One patient exhibited paravalvular leakage and the valve was replaced by a homograft 2 days later. After 6–12 months' follow-up,

the remaining patients had good valvular function. However, this approach requires complete dissection of the heart after full sternotomy.

Dittrich et al. published a report on an 8-year-old boy in whom transverse mini-thoracotomy through the third intercostal space was used to implant an injectable 29 mm stented porcine valve directly into the pulmonary artery bifurcation [32]. The procedure was performed during rapid ventricular pacing and right ventricular unload by a short running femorally implanted cardiopulmonary bypass.

More recently, some authors have reported an interesting subxyphoid hybrid approach as a first-line method for implanting a Melody valve in a 3-year-old boy (12 kg), in whom venous access using the Ensemble® 22 Fr delivery system (Medtronic Inc., Minneapolis, MN, USA) was not feasible [33]. PPVI was uneventful, with excellent valve function on echocardiography, and the patient was discharged 2 days after the procedure. Other authors have reported the use of periventricular pulmonary valve implantations, but only in the setting of complications with the transfemoral approach in adults or larger children [34,35]. One concern is the creation by this periventricular approach of a right ventricular scar, which might lead to an increased incidence of ventricular arrhythmias by the creation of re-entry circuits, especially in tetralogy of Fallot patients [36]. Despite these limitations, hybrid procedure results are very encouraging and this approach may be used increasingly for PVR, whether in small children or in patients with large RVOTs.

### Anticipating percutaneous pulmonary valve implantation during first surgery

Another collaborative approach between surgeons and interventionists is the adjustment of the surgical strategy to further facilitate PPVI. By providing an anatomical substrate for PPVI during the first or second operation, the surgeons may minimize the number of subsequent open-heart procedures. In tetralogy of Fallot, the use of pulmonary valve sparing techniques (i.e. recycling the pulmonary valve or the V-PLASTY technique) should be encouraged, not only to prevent RVOT enlargement and pulmonary insufficiency, but also to allow subsequent PPVI if/when necessary [37,38]. The placement of a GORE-TEX® band (W.L. Gore & Associates, Newark, DE, USA) on the main pulmonary artery to avoid major enlargement is another strategy to consider. Furthermore, surgeons should consider the possibility of PPVI when choosing the size of a bioprosthetic valve or conduit for PVR. Finally, in case of early catheterization procedures in operated children, the placement of a stent in the RVOT may be used to fix the size of the outflow tract for subsequent PPVI.

## Durability of devices

Long-term durability of PPVI devices has not been evaluated so far. Indeed, recent reports have only described medium-term outcomes with these valves [3,4]. To date, no authors have compared the long-term durability of PPVI devices with surgical valves. However, considering its behaviour under high-pressure conditions, the Melody valve seems to be more durable than initially expected [39].

Failure of analogous surgically implanted bioprosthetic valves occurs secondary to deposition of calcium, leading to progressive dysfunction of the valve. Furthermore, it is known that homografts induce a humoral immunological response, which has been correlated with the risk of failure [40,41]. The use of tissue-engineering valved stents may overcome these current limitations. Indeed, tissue-engineered heart valves require no anticoagulation and have the ability to grow and remodel without immunological reaction. Tissue-engineered valves with autologous cells have already been used clinically [42]. In this human study, the authors isolated cells from children's peripheral blood, seeded those cells on a decellularized human pulmonary valve (acellular allograft matrix), placed it into a bioreactor and surgically implanted the new tissue-engineered valve into the children. In the following 3.5 years, the pulmonary valve annulus diameter increased and the valve regurgitation decreased slightly; no signs of valve degeneration have been observed so far.

More recently, Metzner et al. implanted percutaneously similar bioengineered valves sutured on a nitinol self-expanding stent in sheep pulmonary valves. Gross morphology confirmed excellent opening and closure characteristics of all leaflets after 4 weeks, although a mammogram of the stent showed mild annular calcification ( $n=4/7$ ) [43]. One limitation of this method is the absence of valved stent growth ability, although the use of biodegradable stents might solve that issue.

Thin-film nitinol has favourable biological properties as well as elastic properties, which make it an ideal material for use in transcatheter heart valves. Because nitinol also has shape memory, complete heart valves (the leaflets and support structure) can be made entirely from this material. A thin-film nitinol heart valve could be the ideal hybrid valve: it could have the biological compatibility and non-thrombogenicity of tissue valves, and the longevity of a mechanical valve (nitinol has very impressive fatigue properties).

A semilunar thin-film nitinol heart valve has been designed and tested in animals. This eNitinol membrane – PercValve® (Advanced Bioprosthetic Surfaces, Ltd., San Antonio, TX, USA) – has leaflets made from 10  $\mu$ m membranes of thin-film nitinol, which is made to be very flexible by incorporation of multiple regularly-spaced small fenestrations. It is a self-expandable valve that can collapse into a 10-Fr sheath. These valves could have very unique advantages for improving valve durability, as they endothelialize rapidly and could certainly be made to be sufficiently low profile for use even in small infants [44].

## Non-invasive imaging contribution

PPVI suffers from radiation exposure and limited visualization in some complex anatomies. In contrast, magnetic resonance imaging (MRI)-guided cardiac catheterizations involve no exposure to radiation and provide useful additional information regarding intracardiac and vascular anatomy. Various catheter-based interventions frequently used in the field of congenital heart diseases were previously performed in animal studies using MRI guidance [45,46].

In 2010, Tzifa et al. reported the first-in-man solely MRI-guided pulmonary valvuloplasty [47]. Cardiovascular MRI characteristics of both transcatheter heart valves currently commercially available for transcatheter aortic valve implantation (SAPIEN; CoreValve® [Medtronic Inc., Minneapolis, MN, USA]) were assessed in vitro [48].

Clinical translation for PPVI would require further development of the devices to enhance procedure safety. However, MRI-guided PPVI seems promising because of the lack of radiation and additional data provided for soft tissue characterization.

## Conclusion

PPVI has emerged as a safe and effective procedure for the treatment of RVOT dysfunction. Despite the dramatic modifications in the management of patients with dysfunctional RVOT induced by this technology, there are some issues that continue to limit its indications and some unanswered questions regarding its long-term outcome. The development of new PPVI strategies (such as hybrid approaches or MRI-guided procedures), new devices (such as RVOT reducers or the novel Native Outflow Tract device from Medtronic) and new technologies (such as tissue-engineered valved stents) may help to take up these challenges and represent the future of transcatheter pulmonary valve implantation.

## Disclosure of interest

Y. Boudjemline acts as a proctor for Medtronic. The other authors declare that they have no conflicts of interest concerning this article.

## References

- [1] Bonhoeffer P, Boudjemline Y, Saliba Z, et al. Percutaneous replacement of pulmonary valve in a right-ventricle to pulmonary-artery prosthetic conduit with valve dysfunction. *Lancet* 2000;356:1403–5.
- [2] Ringwald JM, Suh EJ. Transcatheter pulmonary valve insertion, expanded use and future directions. *Cardiol Young* 2013;23:910–4.
- [3] Butera G, Milanesi O, Spadoni I, et al. Melody transcatheter pulmonary valve implantation. Results from the registry of the Italian Society of Pediatric Cardiology. *Catheter Cardiovasc Interv* 2013;81:310–6.
- [4] McElhinney DB, Hellenbrand WE, Zahn EM, et al. Short- and medium-term outcomes after transcatheter pulmonary valve placement in the expanded multicenter US melody valve trial. *Circulation* 2010;122:507–16.
- [5] Faza N, Kenny D, Kavinsky C, Amin Z, Heitschmidt M, Hijazi ZM. Single-center comparative outcomes of the Edwards SAPIEN and Medtronic Melody transcatheter heart valves in the pulmonary position. *Catheter Cardiovasc Interv* 2013;82:E535–41.
- [6] Kenny D, Hijazi ZM, Kar S, et al. Percutaneous implantation of the Edwards SAPIEN transcatheter heart valve for conduit failure in the pulmonary position: early phase 1 results from an international multicenter clinical trial. *J Am Coll Cardiol* 2011;58:2248–56.
- [7] Schievano S, Coats L, Miglivaacca F, et al. Variations in right ventricular outflow tract morphology following repair of

- congenital heart disease: implications for percutaneous pulmonary valve implantation. *J Cardiovasc Magn Reson* 2007;9:687–95.
- [8] Boudjemline Y, Brugada G, Van-Aerschot I, et al. Outcomes and safety of transcatheter pulmonary valve replacement in patients with large patched right ventricular outflow tracts. *Arch Cardiovasc Dis* 2012;105:404–13.
  - [9] Boudjemline Y, Legendre A, Ladouceur M, et al. Branch pulmonary artery jailing with a bare metal stent to anchor a transcatheter pulmonary valve in patients with patched large right ventricular outflow tract. *Circ Cardiovasc Interv* 2012;5:e22–5.
  - [10] Malekzadeh-Milani S, Patel M, Boudjemline Y. Folded Melody valve technique for complex right ventricular outflow tract. *EuroIntervention* 2014;9:1237–40.
  - [11] Schievano S, Taylor AM, Capelli C, et al. First-in-man implantation of a novel percutaneous valve: a new approach to medical device development. *EuroIntervention* 2010;5:745–50.
  - [12] Lurz P, Coats L, Khambadkone S, et al. Percutaneous pulmonary valve implantation: impact of evolving technology and learning curve on clinical outcome. *Circulation* 2008;117:1964–72.
  - [13] Therrien J, Provost Y, Merchant N, Williams W, Colman J, Webb G. Optimal timing for pulmonary valve replacement in adults after tetralogy of Fallot repair. *Am J Cardiol* 2005;95:779–82.
  - [14] Momenah TS, El Oakley R, Al Najashi K, Khoshhal S, Al Qethamy H, Bonhoeffer P. Extended application of percutaneous pulmonary valve implantation. *J Am Coll Cardiol* 2009;53:1859–63.
  - [15] Gillespie MJ, Dori Y, Harris MA, Sathanandam S, Glatz AC, Rome JJ. Bilateral branch pulmonary artery melody valve implantation for treatment of complex right ventricular outflow tract dysfunction in a high-risk patient. *Circ Cardiovasc Interv* 2011;4:e21–3.
  - [16] Maschietto N, Milanese O. A concert in the heart: bilateral Melody valve implantation in the branch pulmonary arteries. *J Invasive Cardiol* 2013;25:E69–71.
  - [17] Robb JD, Harris MA, Minakawa M, et al. Melody valve implantation into the branch pulmonary arteries for treatment of pulmonary insufficiency in an ovine model of right ventricular outflow tract dysfunction following tetralogy of Fallot repair. *Circ Cardiovasc Interv* 2011;4:80–7.
  - [18] Cheatham SL, Holzer RJ, Chisolm JL, Cheatham JP. The Medtronic Melody® transcatheter pulmonary valve implanted at 24-mm diameter—it works. *Catheter Cardiovasc Interv* 2013;82:816–23.
  - [19] Schievano S, Migliavacca F, Coats L, et al. Percutaneous pulmonary valve implantation based on rapid prototyping of right ventricular outflow tract and pulmonary trunk from MR data. *Radiology* 2007;242:490–7.
  - [20] Meredith IT, Worthley SG, Whitbourn RJ, et al. Transfemoral aortic valve replacement with the repositionable Lotus Valve System in high surgical risk patients: the REPRISE I study. *EuroIntervention* 2014;9:1264–70.
  - [21] Basquin A, Pineau E, Galmiche L, Bonnet D, Sidi D, Boudjemline Y. Transcatheter valve insertion in a model of enlarged right ventricular outflow tracts. *J Thorac Cardiovasc Surg* 2010;139:198–208.
  - [22] Boudjemline Y, Agnoletti G, Bonnet D, Sidi D, Bonhoeffer P. Percutaneous pulmonary valve replacement in a large right ventricular outflow tract: an experimental study. *J Am Coll Cardiol* 2004;43:1082–7.
  - [23] Mollet A, Basquin A, Stos B, Boudjemline Y. Off-pump replacement of the pulmonary valve in large right ventricular outflow tracts: a transcatheter approach using an intravascular infundibulum reducer. *Pediatr Res* 2007;62:428–33.
  - [24] Amahzoune B, Szymansky C, Fabiani JN, Zegdi R. A new endovascular size reducer for large pulmonary outflow tract. *Eur J Cardiothorac Surg* 2010;37:730–2.
  - [25] Berman DP, McElhinney DB, Vincent JA, Hellenbrand WE, Zahn EM. Feasibility and short-term outcomes of percutaneous transcatheter pulmonary valve replacement in small (< 30 kg) children with dysfunctional right ventricular outflow tract conduits. *Circ Cardiovasc Interv* 2014;7:142–8.
  - [26] Batlivala SP, Emani S, Mayer JE, McElhinney DB. Pulmonary valve replacement function in adolescents: a comparison of bioprosthetic valves and homograft conduits. *Ann Thorac Surg* 2012;93:2007–16.
  - [27] Lindsey CW, Parks WJ, Kogon BE, Sallee 3rd D, Mahle WT. Pulmonary valve replacement after tetralogy of Fallot repair in preadolescent patients. *Ann Thorac Surg* 2010;89:147–51.
  - [28] Menon SC, Cetta F, Dearani JA, Burkhart HA, Cabalka AK, Hagler DJ. Hybrid intraoperative pulmonary artery stent placement for congenital heart disease. *Am J Cardiol* 2008;102:1737–41.
  - [29] Boudjemline Y, Schievano S, Bonnet C, et al. Off-pump replacement of the pulmonary valve in large right ventricular outflow tracts: a hybrid approach. *J Thorac Cardiovasc Surg* 2005;129:831–7.
  - [30] Boudjemline Y, Pineau E, Borenstein N, Behr L, Bonhoeffer P. New insights in minimally invasive valve replacement: description of a cooperative approach for the off-pump replacement of mitral valves. *Eur Heart J* 2005;26:2013–7.
  - [31] Schreiber C, Horer J, Vogt M, et al. A new treatment option for pulmonary valvar insufficiency: first experiences with implantation of a self-expanding stented valve without use of cardiopulmonary bypass. *Eur J Cardiothorac Surg* 2007;31:26–30.
  - [32] Dittrich S, Gloeckler M, Arnold R, et al. Hybrid pulmonary valve implantation: injection of a self-expanding tissue valve through the main pulmonary artery. *Ann Thorac Surg* 2008;85:632–4.
  - [33] Holoshitz N, Ilbawi MN, Amin Z. Perventricular Melody valve implantation in a 12-kg child. *Catheter Cardiovasc Interv* 2013;82:824–7.
  - [34] Berman DP, Burke R, Zahn EM. Use of a novel hybrid approach to salvage an attempted transcatheter pulmonary valve implant. *Pediatr Cardiol* 2012;33:839–42.
  - [35] Simpson KE, Huddleston CB, Foerster S, Nicholas R, Balzer D. Successful subxyphoid hybrid approach for placement of a Melody percutaneous pulmonary valve. *Catheter Cardiovasc Interv* 2011;78:108–11.
  - [36] Zeppenfeld K, Schalij MJ, Bartelings MM, et al. Catheter ablation of ventricular tachycardia after repair of congenital heart disease: electroanatomic identification of the critical right ventricular isthmus. *Circulation* 2007;116:2241–52.
  - [37] Pretre R, Rosser B, Mueller C, Kretschmar O, Dave H. Recycling of the pulmonary valve: an elegant solution for secondary pulmonary regurgitation in patients with tetralogy of Fallot. *Ann Thorac Surg* 2012;94:850–2.
  - [38] Ustunsoy H, Gokaslan G, Ozcaliskan O, et al. ‘‘V-PLASTY’’: a novel technique to reconstruct pulmonary valvular and annular stenosis in patients with right ventricular outflow tract obstruction. *J Cardiothorac Surg* 2013;8:55.
  - [39] Hasan BS, McElhinney DB, Brown DW, et al. Short-term performance of the transcatheter Melody valve in high-pressure hemodynamic environments in the pulmonary and systemic circulations. *Circ Cardiovasc Interv* 2011;4:615–20.
  - [40] Breinholt 3rd JP, Hawkins JA, Lambert LM, Fuller TC, Profaizer T, Shaddy RE. A prospective analysis of the immunogenicity of cryopreserved nonvalved allografts used in pediatric heart surgery. *Circulation* 2000;102:III179–82.
  - [41] Schoen FJ, Levy RJ. Calcification of tissue heart valve substitutes: progress toward understanding and prevention. *Ann Thorac Surg* 2005;79:1072–80.
  - [42] Cebotari S, Lichtenberg A, Tudorache I, et al. Clinical application of tissue engineered human heart valves using autologous progenitor cells. *Circulation* 2006;114:1132–7.

- [43] Metzner A, Stock UA, Iino K, et al. Percutaneous pulmonary valve replacement: autologous tissue-engineered valved stents. *Cardiovasc Res* 2010;88:453–61.
- [44] Levi DS, Kusnezov N, Carman GP. Smart materials applications for pediatric cardiovascular devices. *Pediatr Res* 2008;63:552–8.
- [45] Ratnayaka K, Saikus CE, Faranesh AZ, et al. Closed-chest transthoracic magnetic resonance imaging-guided ventricular septal defect closure in swine. *JACC Cardiovasc Interv* 2011;4:1326–34.
- [46] Raval AN, Telep JD, Guttman MA, et al. Real-time magnetic resonance imaging-guided stenting of aortic coarctation with commercially available catheter devices in Swine. *Circulation* 2005;112:699–706.
- [47] Tzifa A, Krombach GA, Kramer N, et al. Magnetic resonance-guided cardiac interventions using magnetic resonance-compatible devices: a preclinical study and first-in-man congenital interventions. *Circ Cardiovasc Interv* 2010;3: 585–92.
- [48] Kahlert P, Eggebrecht H, Plicht B, et al. Towards real-time cardiovascular magnetic resonance-guided transarterial aortic valve implantation: in vitro evaluation and modification of existing devices. *J Cardiovasc Magn Reson* 2010;12:58.